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THE X-RAY TRANSIENT XTE J1118+480: MULTIWAVELENGTH OBSERVATIONS OF A LOW-STATE MINIOUTBURST

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ABSTRACT

We present multiwavelength observations of the newly discovered X-ray transient XTE J1118+480 obtained in the rising phase of the 2000 April outburst. This source is located at unusually high Galactic latitude and in a very low absorption line of sight. This made the first *Extreme Ultraviolet Explorer* (*EUVE*) spectroscopy of an X-ray transient outburst possible. Together with our *Hubble Space Telescope*, *Rossi X-Ray Timing Explorer*, and United Kingdom Infrared Telescope data, this gives unprecedented spectral coverage. We find the source in the low hard state. The flat IR-UV continuum appears to be a combination of optically thick disk emission and possibly synchrotron, while at higher energies (including EUV), a typical low hard state power law is seen. *EUVE* observations reveal no periodic modulation, suggesting an inclination low enough that no obscuration by the disk rim occurs. We discuss the nature of the source and this outburst and conclude that it may be more akin to minioutbursts seen in GRO J0422+32 than to a normal X-ray transient outburst.

Subject headings: accretion, accretion disks — binaries: close — stars: individual (XTE J1118+480) — ultraviolet: stars — X-rays: stars

1. INTRODUCTION

Soft X-ray transients, also known as X-ray novae (Tanaka & Shibazaki 1996), are low-mass X-ray binaries in which long periods of quiescence—typically decades—are punctuated by very dramatic X-ray and optical outbursts, often accompanied by radio activity. In a prototypical outburst, the luminosity approaches the Eddington limit and X-ray emission is dominated by thermal emission from the hot inner accretion disk. Optical emission is then thought to be produced by reprocessing of X-rays. There are exceptions, however, and some outbursts never show disk X-ray emission (e.g., GRO J0422+32; see Nowak 1995 for summary and discussion).

XTE J1118+480 was discovered by *Rossi X-Ray Timing Explorer* (*RXTE*) on 2000 March 29 (Remillard et al. 2000) as a weak, slowly rising X-ray source. Analysis of earlier data revealed an outburst in 2000 January reaching a similar brightness. A power-law spectrum was seen to at least 120 keV (Wilson & McCollough 2000), with spectral index similar to Cyg X-1 in the low hard state. A 13th magnitude optical counterpart was promptly identified, coincident with an object with red magnitude 18.8 in Sky Survey images (Uemura, Kato, & Yamaoka 2000a; Uemura et al. 2000b). The optical spectrum was typical of X-ray novae in outburst (Garcia et al. 2000). Continued observations revealed a weak photometric modulation on a 4.1 hr period (Cook et al. 2000). The optical brightness is surprising, since the X-rays are so faint. It was suggested that the system might be at very high inclination, so that the X-ray source was obscured by the disk rim and only scattered X-rays are visible (Garcia et al. 2000). A radio counterpart was also discovered with flux 6.2 mJy (Pooley & Waldram 2000).

XTE J1118+480 has a very high Galactic latitude ($b = +62°$) and is close to the Lockman Hole (Lockman, Jahoda, & McCammon 1986). Consequently, it has a very low interstellar absorption of $E(B-V) \lesssim 0.024$ (Garcia et al. 2000). This, together with its brightness, make XTE J1118+480 an ideal target for multiwavelength coverage. The observations described here were performed as part of a coordinated multiwavelength campaign. A highlight of the campaign is that the low interstellar absorption allowed the first *Extreme Ultraviolet Explorer* (*EUVE*) spectroscopy of an X-ray transient. This campaign is still underway, so we report here only our earliest observations of 2000 April 4–18.

2. *EUVE* DATA

EUVE observations of XTE J1118+480 took place during 2000 April 8.10–8.71, 13.32–13.93, and 16.91–19.60 UT. For a description of the *EUVE* satellite and instrumentation, refer to Bowyer & Malina (1991), Abbott et al. (1996), and Sirk et al. (1997). The deep survey (DS) photometer achieved net exposures of 0.93, 0.90, and 6.92 ks, limited by shutdowns due to high background levels. The short-wavelength (SW) spectrometer was not affected by such shutdowns and achieved net exposures of 19.4, 19.8, and 81.1 ks. The bandpasses of the DS photometer and SW spectrometer are defined by a Lexan/Boron filter and extend from ≈70 to 180 Å, although interstellar absorption extinguishes the flux longward of about 120 Å. The second and third observations were offset-pointed to recover more of the short-wavelength flux.

The mean background-subtracted DS count rates for the three visits do not vary by much: 1.61, 1.51, and 1.62 counts s^{-1}. Individual light curves show statistically significant variability about the mean (e.g., Fig. 1; χ^2/degrees of freedom = 99.3/41 = 2.42). To determine if this variability is correlated with orbital phase, we folded the data from the April 18 observation on the optical photometric period of 0.17082 days (Patterson 2000), with $T_0 = 647.663 \pm 0.004$ (HJD) corresponding to optical maximum (J. Patterson 2000, private communication). The resultant light curve is shown in the inset of

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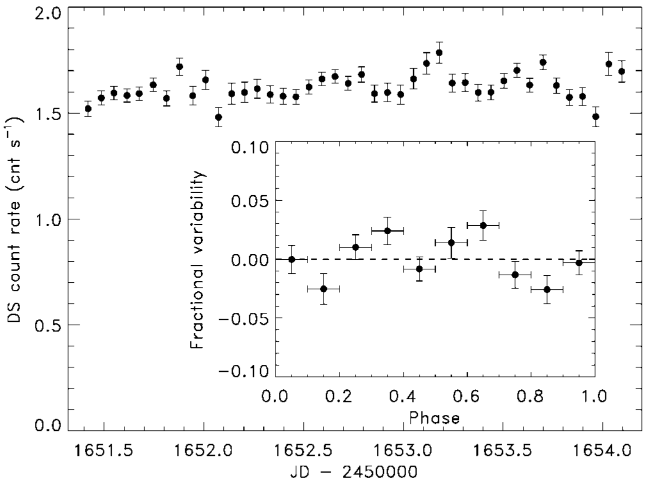

FIG. 1.—*EUVE*/DS light curve from 2000 April 18. The error bars are the 1 σ count rate errors from the photon statistics. The inset shows the same data folded on the period of Patterson (2000), binned into 10 phase bins and converted to fractional variations about the mean.

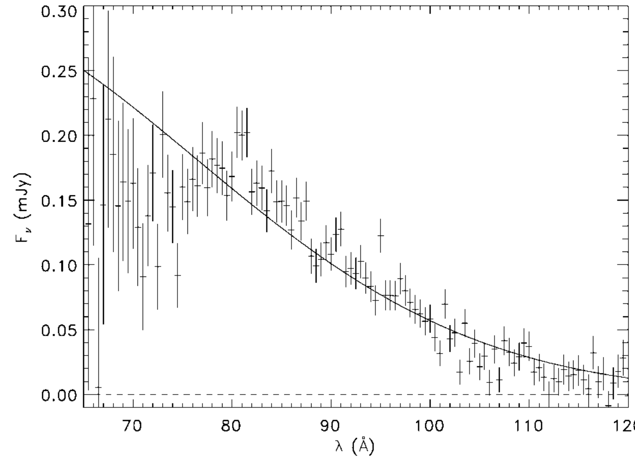

FIG. 2.—Mean *EUVE*/SW spectrum from 2000 April 18. The vertical error bars are the 1 σ errors from the photon statistics. The fit is constant νF_ν subject to photoelectric absorption.

Figure 1. There is no evidence for a modulation in the EUV flux of greater than 6% full amplitude on this period. We also performed a period search on these data but found no period significant at the 90% level, for 3 hr $< P <$ 4 days.

Figure 2 shows the background-subtracted mean *EUVE* SW spectrum from the April 18 observation binned to $\Delta\lambda = 0.5$ Å, matching the spectral resolution of the instrument, and removing the nonstatistical correlation between neighboring wavelength bins. The short-wavelength limit of the spectrum is dictated by the strong increase in the background shortward of ~70 Å, while interstellar photoelectric absorption suppresses the flux longward of ~120 Å. To approximately constrain the absorbing column density and flux, we fit these data with constant νF_ν and photoelectric absorption. For the latter, we used the EUV absorption cross sections of Rumph, Bowyer, & Vennes (1994) for H I, He I, and He II with abundance ratios 1 : 0.1 : 0.01, typical of the diffuse interstellar medium. The resulting fit parameters and 90% confidence errors are $\nu F_\nu = (2.5^{+0.2}_{-0.3}) \times 10^{-10}$ ergs cm^{-2} s^{-1} and $N_{\rm H} = (7.4 \pm 0.4) \times 10^{19}$ cm^{-2}, with χ^2/degrees of freedom = 206.2/105 = 1.96. The fit is poor because the data systematically fall below this simple model shortward of ~75 Å, either because of a flattening of the continuum spectrum or an absorption feature or edge. There may also be a broad emission feature at ~81 Å. We cannot usefully constrain the slope of the EUV spectrum but assuming a wide range of intrinsic EUV spectra, $+2 \geq \alpha \geq -4$, where $F_\nu \propto \nu^\alpha$, gives a range of column densities of (0.35–1.15) × 10^{20} cm^{-2}, respectively. These values are relatively low and are fully consistent with the expected column density of the interstellar medium in the vicinity of the Lockman Hole, (0.5–1.5) × 10^{20} cm^{-2} (B. Y. Welsh 2000, private communication). There does not therefore appear to be any strong absorption intrinsic to the source, although estimates from fits to the *EUVE* spectrum are sensitive to the assumed ionization state of the absorber.

The low intrinsic absorption implied by the EUV spectrum together with the lack of orbital modulation is evidence against a high-inclination explanation for the low X-ray–to–optical flux ratio (Garcia et al. 2000). In that case, because of the extreme sensitivity of the EUV flux to absorbing material, we would expect some modulation due to asymmetry in the disk rim and significant intrinsic absorption by material above the disk. It instead appears likely that the central disk regions are unobscured and that the system is in an intrinsically X-ray–faint state. This is also consistent with the lack of optical eclipses. This argument does, however, assume that EUV emission originates from the disk. If it actually comes from a wind, as in the cataclysmic variable OY Car (Mauche & Raymond 2000), for example, then the system could still be at high inclination.

3. *HUBBLE SPACE TELESCOPE* AND UNITED KINGDOM INFRARED TELESCOPE DATA

Hubble Space Telescope (*HST*) observations were performed with the Space Telescope Imaging Spectrograph on 2000 April 8.52–8.81 and 18.57–18.74 UT using the E140M, E230M, G430L, and G750L modes. An average calibrated spectrum for April 8 was constructed from standard *HST* pipeline data products, with useful coverage from 1150 to 10000 Å. The region from 1195 to 1260 Å was excluded as this was completely dominated by N V emission and Lyα absorption (Haswell, Hynes, & King 2000a).

Near-infrared observations were carried out at the United Kingdom Infrared Telescope (UKIRT) 3.8 m telescope using UFTI (1–2.5 μm) and IRCAM/TUFTI (1–5 μm) on 2000 April 4 and 18. Images were obtained in *JHK* with UFTI and *JHKL′M′* with IRCAM/TUFTI. Exposure times were 10–60 s, and the conditions were photometric. The images were processed by removal of the dark current, flat-fielding, and sky subtraction. The magnitudes acquired on April 4.2 UT with UFTI are $J = 12.12 \pm 0.02$, $H = 11.75 \pm 0.02$, and $K = 11.06 \pm 0.02$ (Chaty et al. 2000). The magnitudes acquired on April 18.5 UT with IRCAM/TUFTI are $J = 11.92 \pm 0.07$, $H = 11.43 \pm 0.06$, $K = 11.05 \pm 0.08$, $L' = 9.71 \pm 0.14$, and $M' = 9.38 \pm 0.42$. The source brightened between these two dates, which bracket the dates of *HST* observations described above.

From UV to IR wavelengths (~1000–50000 Å) the spectrum is flat with $F_\nu = 24$ mJy, constant to within 10%, although a weak Balmer jump in absorption of ~7% is present. This likely indicates that some optically thick disk emission is present. The underlying flat continuum, however, does not resemble a disk spectrum, as is discussed in § 5.

4. *RXTE* DATA

We observed XTE J1118+480 with the *RXTE* Proportional Counter Array (PCA) and High-Energy Timing Experiment (HEXTE) at several epochs selected to coincide with the *HST* visits. This included 2000 April 8.55–8.58 when a total exposure of about 4 ks was obtained. Subsequent discussion refers to that observation.

For the PCA, we used the "standard mode" data (128 spectral channels, 16 s accumulations), selecting subintervals when the number of detectors on remained constant (about 75% of the total). The current PCA background model and/or the instrument responses are unreliable above about 25 keV, so we did not use those channels for our model fitting. There was sufficient PCA-HEXTE overlap so that this was not a serious limitation. The lowest several energy channels are also known to be problematic and so were discarded. The total flux on the 2–10 keV band was about 1.0×10^{-9} ergs cm^{-2} s^{-1}, i.e., about 40 mcrab. For HEXTE, the exposure time was rather marginal for detailed spectral modeling given the source intensity relative to the background, but the source seems to be solidly detected to ∼80 keV and perhaps above 100 keV.

The data sets were then simultaneously deconvolved to derive a best estimate of the incident photon flux. Given the known cross calibration discrepancies between the two instruments, we allowed the two normalization terms to vary independently. The spectrum is hard, with a photon power-law index of about 1.8 ± 0.1. A thermal Comptonization model (Sunyaev & Titarchuk 1980) with $\tau = 3.2$ and $kT_e = 33$ keV also provided an acceptable fit. In both cases, there was a distinct positive residual corresponding to the 6.4 keV Fe K resonance, thus a Gaussian line profile was included to refine our overall fit. Given the low hydrogen column density and our lack of low-energy coverage, the effect of interstellar absorption on the X-ray spectrum is negligible. There was no evidence (in terms of statistical improvement to our fits) for a soft-excess component.

5. THE SPECTRAL ENERGY DISTRIBUTION

Figure 3 shows the spectral energy distribution (SED) inferred from radio to hard X-ray data. Radio data obtained with the VLA and Ryle telescopes between 2000 April 2.74–3.13 were reported by Dhawan et al. (2000). Between then and April 18, the radio was no more than 30% brighter, i.e., $\Delta \log F_\nu \lesssim 0.1$ (G. Pooley 2000, private communication). UKIRT data were obtained on April 4 and 18 and are consistent to within $\Delta \log F_\nu \sim 0.15$. The other data were obtained simultaneously during April 8. Calibration errors in the *HST* and *RXTE* data are estimated at $\Delta \log F_\nu \lesssim 0.1$. The *EUVE* uncertainty is dominated by the uncertain absorption as shown.

These data have been corrected for interstellar absorption where necessary. Assuming the column density inferred above to be interstellar and adopting an average gas-dust ratio (Bohlin, Savage, & Drake 1978) and extinction curve (Seaton 1979), we corrected the IR-UV data for reddening with $E(B-V) = 0.013$. This makes only a small difference at these wavelengths because the value is so low. The assumed absorption is important at EUV wavelengths, so for the *EUVE* data we plot three solutions with $N_H = 0.35$, 0.75, and 1.15×10^{20} cm^{-2} to illustrate how the flux and spectral index vary with assumed absorption.

The presence of a Balmer jump in the *HST* optical data suggests that an optically thick disk makes a significant con-

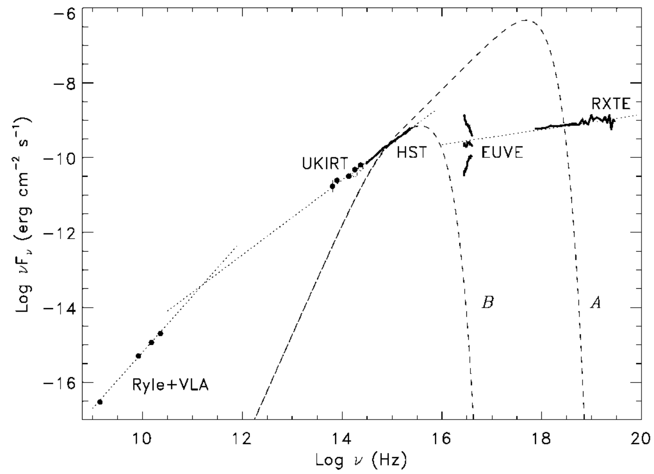

FIG. 3.—Spectral energy distribution from radio to hard X-ray frequencies on 2000 April 8 (*HST, EUVE, RXTE*), April 2–3 (radio), and April 4, 18 (UKIRT). *EUVE* data are shown corrected for three different amounts of absorption. Dashed lines are two steady state disk models with differing inner radii. Dotted lines are characteristic power laws ($F_\nu \propto \nu^\alpha$; from left to right, $\alpha = +0.5$, 0.0, -0.8). See text for details.

tribution there. Figure 3 shows model SEDs calculated for a steady state viscously heated disk (Shakura & Sunyaev 1973). These are intended to be schematic rather than detailed fits. The low-energy cutoff is fixed by an outer temperature of 8000 K, chosen to be consistent with the hot phase of the disk instability model. The high-energy cutoff then depends on the inner radius: $\sim 3R_S$ and $\sim 2000R_S$ for models A and B, respectively (these assume an orbital period of 4.1 hr and a 7 $M_\odot$ black hole as the accretor). Model A is representative of a high-state SED, with the disk extending to the last stable orbit. This is clearly ruled out by the EUV and X-ray data as a direct consequence of the low X-ray–to–optical flux ratio. The uncertainty in the system parameters, including the possibility that the central object is a neutron star, cannot resolve this. Model B is more like the low hard state scenario proposed by Esin, McClintock, & Narayan (1997) in which the center of the disk (out to 10^3–10^4 R_S) is evaporated into an advective flow. This model is consistent with the low X-ray–to–optical flux ratio and reproduces the UV slope fairly well. The EUV–to–hard X-ray range can be approximately fitted by a single power law, $F_\nu \propto \nu^{-0.8}$, typical of the low hard state, and so would not be disk emission. This spectral region does resemble the low hard state SEDs presented by Esin et al. (1997), as does the X-ray–to–optical flux ratio. Alternative explanations of this low flux ratio include material leaving the system in an outflow (e.g., Blandford & Begelman 1997), or accumulating at larger radii in a non–steady state disk; either option will reduce the central accretion rate as required.

Disk models provide a very poor fit in the IR, as a disk spectrum should steepen to a Rayleigh-Jeans tail well before the M' band is reached (unless the edge of the disk is at $T \lesssim 1000$ K). It thus appears that another source of near-IR flux is present. This may be related to the radio emission, as this lies close to an extrapolation of the IR-UV power law. The very flat IR-UV part of the SED ($F_\nu \sim$ constant) could then very naturally be interpreted as a mixture of an optically thick disk spectrum and flat-spectrum emission, possibly synchrotron, such as is seen at radio-millimeter wavelengths in Cyg X-1 and other black hole candidates (Fender et al. 2000).

The radio emission has a steeper, inverted spectrum ($F_\nu \propto \nu^{0.5}$), likely optically thick synchrotron emission.

6. DISCUSSION

Consideration of the spectral energy distribution suggests that during the period 2000 April 4–18 the source was in the low hard state. Power density spectra at X-ray, UV, and optical wavelengths support this, showing band-limited noise and quasi-periodic oscillations typical of this state (Revnivtsev, Sunyaev, & Borozdin 2000; Haswell et al. 2000b). This in itself is not particularly striking: GRO J0422+32, for example, spent its entire 1992–1993 main outburst in the low hard state. What is striking is the low X-ray–to–optical flux ratio: it is an unusually low state. This is not typical of a major soft X-ray transient outburst. There are, however, similarities in this behavior to *minioutbursts* in GRO J0422+32 (Castro-Tirado, Ortiz, & Gallego 1997; Shrader et al. 1997). Like the outbursts of XTE J1118+480, these outbursts were characterized by a very low X-ray–to–optical flux ratio and low hard state behavior. The optical outbursts have comparable length and brightness; in GRO J0422+32 the minioutburst duration is ∼60 days with ∼120 day recurrence time. In XTE J1118+480 the first outburst lasted ∼40 days, with the second outburst beginning ∼60 days after the start of the first. In both cases, the peak optical brightness is ∼6 mag above quiescence, with the interoutburst brightness about 3.5 mag above quiescence in XTE J1118+480 (Uemura et al. 2000b) and 1–3 mag above quiescence in GRO J0422+32. It thus appears likely that the outburst of XTE J1118+480 is of the same kind as the minioutbursts in GRO J0422+32, suggesting that this phenomenon is not just an aftereffect of a main outburst, but can occur in isolation.

The nature of the compact object remains uncertain. The spectral energy distribution is equivocal, as both black hole and neutron star systems can show extended power laws in the low hard state, with similar photon indices (Barret et al. 2000 and references therein). A distinguishing neutron star feature may be a very soft excess, $kT \sim 0.5$ keV, associated with the heated neutron star surface or boundary layer; however, our data clearly cannot address this. We note that Revnivtsev et al. (2000) have speculated that the compact object is a black hole based on the nondetection of high-frequency variability, which is considered a signature of a neutron star.

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